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(54) **A method for detecting a roll rate sensor fault**

(57)   A control system (18) for an automotive vehicle (19) having a vehicle body includes a sensor cluster having a housing oriented within the vehicle body. A roll rate sensor (31) is positioned within the housing and generates a roll rate sensor signal corresponding to a roll angular motion of the sensor housing. A controller (26) receives the roll rate sensor signal and generates a reference roll angle. The controller (26) also compares the reference roll angle to the roll rate sensor signal and generates a roll rate sensor fault signal in response to a fault determined in said roll rate sensor.
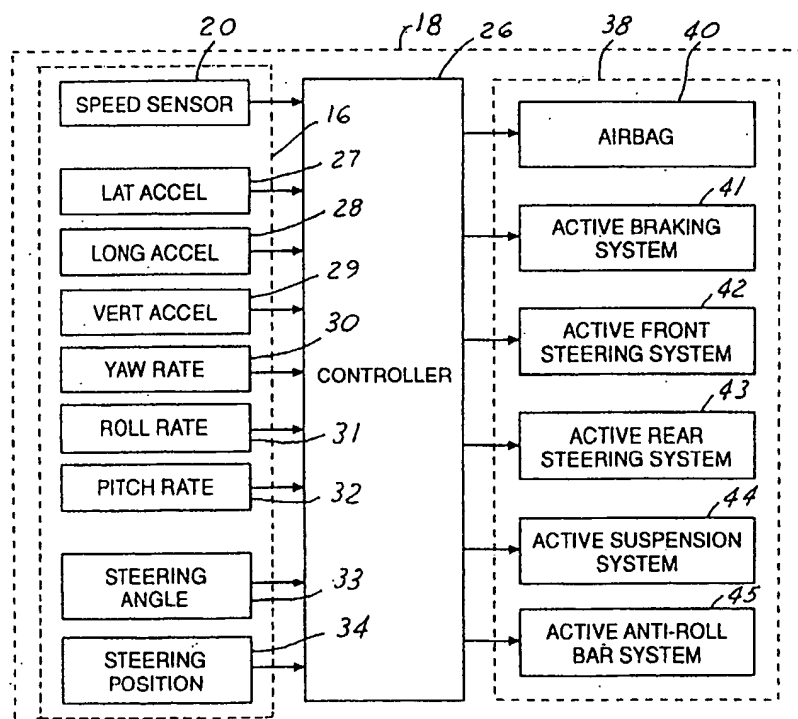
FIG.2

Description

RELATED APPLICATION

5   [0001]   The present invention claims priority to provisional application no. 60/400,155 filed on August 1, 2002, the disclosure of which is incorporated by reference herein.

Technical Field

10   [0002]   The present invention relates generally to automotive vehicle sensors, and more specifically, to a method and apparatus for detecting a roll rate sensor fault.

Background

15   [0003]   Current, rollover stability control (RSC) schemes address vehicle roll and include a variety of sensors sensing vehicle dynamic conditions. RSC systems further include a controller controlling a distributed brake pressure for reducing a tire moment such that the net moment of the vehicle is counter to the vehicle roll direction.
      [0004]   The RSC sensors include a speed sensor, a lateral acceleration sensor, a roll rate sensor, and a yaw rate sensor. The roll rate sensor is typically utilized to estimate the roll angle and to calculate the desired control pressure.
20   Fault modes of the roll rate sensor, therefore, may cause unintended braking, reduced performance or even loss of stability. Such fault modes must be rapidly diagnosed and indicated so that the RSC system is shut down.
      [0005]   U.S. Pat. No. 6,315,373 addresses a similar issue of fault detection for a roll control device. It, however, merely addresses the detection of a lateral accelerometer in a system that uses lateral acceleration signals to detect vehicle roll over stability, which is insufficient for a comprehensive RSC system. Furthermore, this method relies heavily on
25   the vehicle suspension model. Variations of the suspension parameters, such as the spring stiffness and damping ratio, may cause an unnecessary false warning (i.e. false positive) or a missed detection (i.e. false negative).
      [0006]   It is therefore desirable to provide a system that rapidly detects a roll rate sensor fault in a rollover stability control system that can be applied to various vehicle platforms without tuning. This method should also be able to detect a fault independent of the specific fault modes as well as detect a fault that is otherwise not detectable by
30   checking electrical specifications.

Summary of the Invention

      [0007]   In one aspect of the invention, a control system for an automotive vehicle having a vehicle body includes a
35   sensor cluster having a housing oriented within the vehicle body. A roll rate sensor is positioned within the housing and generates a roll rate sensor signal corresponding to a roll angular motion of the sensor housing. A controller receives the roll rate sensor signal and generates a reference roll angle. The controller also compares the reference roll angle to the roll rate sensor signal and generates a roll rate sensor fault signal in response a fault determined in said roll rate sensor.
40   [0008]   In a further aspect of the invention, a method for detecting a roll rate sensor fault includes generating a reference roll angle, generating a roll rate sensor signal, comparing the reference roll angle to the roll rate sensor signal, and generating a roll rate sensor fault signal.
      [0009]   One objective of the present invention is to provide a method for fault detection of a roll rate sensor onboard a vehicle. Sensor fault is not always detectable by sensor self test and/or system electronic monitoring, having detection
45   relying on the fault to violate sensor specification. Because an in-range signal fault may occur, a redundancy check is included for a safety critical system. The proposed methodology is to provide such a redundancy check through software/analytical redundancy.
      [0010]   The present invention utilizes steering wheel angle, yaw rate, lateral acceleration, and vehicle speed signals to verify roll rate signal. Following the detection, the system, utilizing the roll rate signal may decide to directly shutdown,
50   slowly shutdown, or use a different signal to operate in order to minimize negative effect.
      [0011]   The present invention utilizes both kinematics and dynamics relations among sensor signals and is robust to variation of suspension parameters and unavoidable biases in reference signals. It detects faults independent of the specific fault mode and detects faults that are otherwise not detectable.
      [0012]   Other advantages and features of the present invention will become apparent when viewed in light of the
55   detailed description of the preferred embodiment when taken in conjunction with the attached drawings and appended claims.

Brief Description Of The Drawings

[0013] Figure 1 is a diagrammatic view of a vehicle with variable vectors and coordinator frames in accordance with one embodiment of the present invention.

[0014] Figure 2 is a block diagram of the vehicle sensor system from Figure 1.

[0015] Figure 3 is a logic flow diagram of a method for signal compensation of the roll rate signal for all 'valid' biases in accordance with another embodiment of the present invention.

[0016] Figure 4 is a logic flow diagram of a method for detecting a roll rate sensor fault in accordance with another embodiment of the present invention.

Description Of The Preferred Embodiment

[0017] In the following figures the same reference numerals will be used to identify the same components. The present invention is preferably used to detect roll rate sensor fault in conjunction with a dynamic control system for an automotive vehicle, such as a yaw control system or a rollover control system. However, the present invention may also be used to detect roll rate sensor fault in any vehicle system including a roll rate sensor.

[0018] Referring to Figures 1 and 2, a safety system 18 for an automotive vehicle 19 having a sensing system 16 (sensing cluster), including a roll rate sensor 31, and a controller 26, is illustrated. Various forces and moments are acting thereon during a rollover condition.

[0019] The vehicle safety system 18 includes the sensor system 16. The sensing system 16 may use a six control sensor set including three axial accelerometers including a lateral accelerometer 27, a longitudinal accelerometer 28, and a vertical accelerometer 29 and three axial rotation rate detectors including a yaw rate sensor 30, a roll rate sensor 31, and a pitch rate sensor 32. The sensor system 16 further includes various other sensors, such as wheel speed sensors 20, a steering angle sensor 33 (hand-wheel sensor), and steering angle position sensors 34 (road-wheel sensors). The various sensors will be further described below.

[0020] The vehicle safety system 18 includes the roll rate sensor 31 positioned within the housing of the vehicle safety system 18. The roll rate sensor 31 generates a roll rate sensor signals corresponding to a roll angular motion of the sensor housing.

[0021] The vehicle safety system 18 also includes the controller 26. The controller 26 receives the roll rate sensor signals, generates a reference roll angle, and compares the reference roll angle to the roll rate sensor signal. The controller also generates a roll rate sensor fault signal in response to a fault determined in the roll rate sensor.

[0022] Based upon inputs from the sensor system 16, the controller 26 may control a safety device 38. Depending on the desired sensitivity of the system and various other factors, not all the sensors is used in a commercial embodiment. The safety device 38 may control an airbag 40 or a steering actuator or braking actuator at one or more of the wheels of the vehicle. Also, other vehicle components such as a suspension control 48 are used to adjust the suspension to prevent rollover. Suspension control 48 may include an anti-roll bar.

[0023] Generally, the vehicle 19 has a weight represented as Mg at the center of gravity of the vehicle 19, where $g=$ 9.8 m /s^2 and M is the total mass of the vehicle 19.

[0024] The reference roll angle, a vehicle roll angle in the inertial frame (or the angle between vehicle body lateral axis and the horizon), is obtained with available signals other than roll rate, which is the signal to be verified. This roll angle is an independent reference (from roll rate) of vehicle (global) roll angle, and is therefore termed the "reference roll angle".

[0025] In one embodiment of the present invention, the reference roll angle is generated within the controller 26 through the kinematics relationship between lateral acceleration, yaw rate, vehicle longitudinal speed, and vehicle roll angle are utilized. In other words,

$$\sin \hat{\varphi} = (u \cdot r - a_y)/g \, ,$$

where φ is roll angle, u is vehicle speed, r is yaw rate, g is gravity constant and a_y is lateral acceleration.

[0026] The reference roll angle is generated by applying steering wheel angle information to reduce the approximation error due to the negligence of the dynamic lateral velocity derivative in the above equation. Another embodiment of the present invention includes generating a reference roll angle using steering wheel angle from the steering angle sensor 33 or steering position sensor 34, yaw rate from the yaw rate sensor 30, lateral acceleration from the lateral acceleration sensor 27, and vehicle longitudinal speed from the speed sensor 20.

[0027] Alternately, the dynamic relation between lateral acceleration experienced by the vehicle body and suspension roll motion is used to generate the reference roll angle. The equation representation thereof is:

$$\frac{d}{dt}\begin{bmatrix} \varphi \\ \dot{\varphi} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -K & -C \end{bmatrix}\begin{bmatrix} \varphi \\ \dot{\varphi} \end{bmatrix} + \begin{bmatrix} 0 \\ M/I*H \end{bmatrix}a_y.$$

[0028] After obtaining the reference roll angle, the roll rate signal is compensated within the controller 26 for all 'valid' signal biases.

[0029] A 'valid' signal bias refers to a bias that may occur due to either an electrical noise within sensor specification and/or due to a mechanical disturbance from maneuvers/road conditions.

[0030] For example, a vehicle pitch angle during a turn will induce a measurement bias due to the difference between inertial frame and rotational frame. To illustrate:

$$\dot{\phi} = \omega_x + \sin\phi.\tan\theta.\omega_y + \cos\phi.\tan\theta.\omega_2$$

where $\dot{\phi}$ is Euler roll rate (inertial frame), ω_x, ω_y, and ω_2 are the rotational rate of the body-fixed coordinate. That is, ω_x is the roll rate sensor measurement, ω_z is the yaw rate sensor measurement, and ϕ is the roll angle of interest. Since vehicle roll angle is generally small, the system 18 is concerned with only the third term (of the right hand side) which is a product of vehicle yaw rate and vehicle pitch angle. That is,

$$\dot{\phi} \approx \omega_x + \tan\theta\cdot\omega_z$$

[0031] (Important to note is that when a roll rate fault does occur during a turning maneuver, the compensation mechanism may attempt to compensate the biased roll rate signal by adapting the pitch angle in the above equation.)

[0032] The vehicle roll rate signal averages to zero over a long period of time, therefore, electrical long term bias over time with a minute adjustment at each sampling time.

[0033] Similarly, the mechanical, long-term sensor alignment pitch angle is controlled with a minute adjustment at each sampling time during vehicle turning (i.e. $\omega_z \neq 0$) Because chattering is warranted with this approach, the adjustment should be small enough to prevent the chattering magnitude from exceeding the desired accuracy. The small adjustment restricts the adaptation speed. One skilled in the art will realize that the minute adjustment is only one possible embodiment of adjustment, and that numerous other methods are included in the present invention. Other adjustments, such as sliding mode control based on the basic logic/assumption described above, can be applied.

[0034] Referring to FIGURE 3, a logic flow diagram 70 of signal compensation of the roll rate signal for all 'valid' biases is illustrated. Logic starts in operation block 72 where the signals to be processed are pre-filtering (e.g. with a low pass filter).

[0035] In operation block 74, current vehicle conditions are checked. In other words, a determination is made whether the yaw rate signal is of significant magnitude such that the signal to noise ratio in the subsequent calculation is meaningful and if current vehicle condition is appropriate to assume zero roll rate.

[0036] In inquiry block 76, a check is made whether a fault has already been detected. For a positive response, in operation block 78, roll rate compensation/pitch alignment estimation is stopped if a fault flag is set or is suspected to prevent unneeded and unwanted compensation.

[0037] Otherwise, in operation block 80, a compensation for electrical bias occurs with minute adjustments through logic, such as:

rollrate_compensated = rawrollrate - offset_straight - (yawrate*RAD2DEG)*spa_est;

spa_est -= p_SPA_DELTA * (sign(rollrate_compensated*yawrate)) ;

spa_est = min(MAX_SPA, max(MIN_SPA, spa_est)), where spa_est is the sine of the pitch angle.

[0038] In operation block 82, the sine pitch estimation is low pass filtered to minimize undesirable chattering noises, through logic such as:

1pf_spa = k*1pf_spa + (1-k)*spa_est.

[0039] In operation block 84, the total roll rate offset due to both electrical bias (offset_straight) and mechanical bias (1pf_spa and yawrate).is calculated through logic, such as:

offset_dynamic=offset_straight+(yawrate*RAD2 DEG)*(1pf_spa).

[0040] In operation block 86, the offset straight is updated during straight line driving (i.e. when the turning condition of operation block 74 is not met) through logic as follows:

rollrate_compensated=rawrollrate-offset_straight;

offset_straight+=p_RR_DELTA*(sign(rollrate_c ompensated)).

[0041] Referring again to Figures 1 and 2, the compensated roll rate signal is compared, within the controller 26, with the reference roll angle through kinematics relation and the dynamic interaction related by vehicle suspension. During the comparison, a fault is not declared under a plausible bias due to imperfect compensation (of electrical/ mechanical disturbances) nor when the accuracy of reference vehicle roll angle is in question.

[0042] The controller 26 compares a high pass filtered reference roll angle to a high pass filtered version of the integration of the compensated roll rate signal. When the two differ and the latter signal is nonzero, a fault is suspected.

[0043] The controller 26 compares a low pass filtered version of the derivative of the reference roll angle to the compensated roll rate signal. When the two differ and the roll rate is nonzero, a fault is suspected.

[0044] The controller 26 ideally includes a Kalman filter utilizing the suspension dynamic relation between roll angle acceleration, roll angle rate, and roll angle to compare the reference roll angle and the compensated roll rate.

[0045] The present invention designs an observer utilizing both the suspension dynamics and kinematics relationship between roll angle and rate. The present invention is robust to suspension parameters variations/uncertainties.

[0046] The present invention can be described as a mass-spring system, i.e.:

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ -k & -c \end{bmatrix} x + \begin{bmatrix} 0 \\ 1 \end{bmatrix} d, \qquad x = \begin{bmatrix} \phi \\ \dot{\phi} \end{bmatrix},$$

and

$$y = \begin{bmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{bmatrix} x + f,$$

where k is the (torsional) spring stiffness, or roll stiffness of the suspension, and c is the (roll) damping coefficient (of the suspension). Because the roll stiffness and damping of a vehicle maybe nonlinear and may vary between vehicles and between configurations, these parameter uncertainties are lumped into another term in the aforementioned equation as d and are viewed as disturbances. Because the measurement can be defined as any linear combination of roll angle and roll rate, the C matrix in the equation above is left as design parameters.

$$\hat{y} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \hat{x},$$

[0047] Additionally,

$$\dot{\hat{x}} = \begin{bmatrix} 0 & 1 \\ -k & -c \end{bmatrix} \hat{x} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} (y - \hat{y}),$$

and

$$residue = [1\ -1](\ y - \hat{y}),$$

therefore, it can be shown that

$$TFp_{d \to residue} \equiv 0$$

$$TF_{roll\_angle\_err \to residue} = \frac{s}{s+1},$$

and

$$TF_{roll\_rare\_err \to residue} = -\frac{1}{S+1}$$

[0048]   Defining the observer output as 'residue' causes a roll rate fault to appear as a residue in the observer output while a roll angle 'measurement' error appears as only a transient noise. Moreover, suspension characteristic changes, modeled as disturbance d, do not affect the observer output. Resultantly the same observer design can be applied to various vehicle platforms without tuning.

[0049]   If the residue exceeds a pre-calibrated threshold, (which can be a pre-calibrated function of vehicle dynamic status,) a fault is suspected.

[0050]   If a fault condition is indicated during the aforementioned comparison for a short period of time, having a pre-calibrated length, during which time the system did not detect any fault from the source signal that generated reference roll angle, then a roll rate sensor fault is concluded. Alternately, to facilitate a faster detection, a condition is added to check if roll rate signal is away from zero (which is the normal value) during this period.

[0051]   Special fault detection: for sticky signal fault such that the roll rate signal sticks to a constant value, the following logic is developed:

   If (abs(high pass filtered rollrate) < threshold_1 holds true for more than a precalibrated constant. (abs(high pass filtered suspension roll angle (from lateral acceleration))> threshold_2) holds true for more than a precalibrated constant (not necessarily continuously),

   then a fault is suspected. If this suspected situation has happened for more than a precalibrated number of times, set the fault flag.

[0052]   Following detection of a roll rate sensor fault, the controller 26 responds by either shutting down the safety system 18 or any of the sub-systems of the safety system 18, such as roll-over control and compensation. Alternately, the controller 26 responds to roll rate sensor error by compensating for information that would normally be obtained from the roll rate sensor 31. In one embodiment, the controller 26 compensates for the roll rate sensor using signals from a combination sensors including, but not limited to: the lateral accelerometer 27, the longitudinal accelerometer 28, the vertical accelerometer 29, the yaw rate sensor 30, the pitch rate sensor 32, the wheel speed sensors 20, the steering angle sensor 33 (hand-wheel sensor), and steering angle position sensors 34 (road-wheel sensors). Regardless of the controller response to roll rate fault, a further embodiment of the present invention includes a driver notification of roll rate sensor problems.

[0053]   Referring now to Figure 4, a logic flow diagram 100 of a method for detecting a roll rate sensor fault is illustrated. Logic starts in operation block 102, where a reference roll angle is generated from available signals other than the roll rate signal, as was discussed previously.

[0054]   In operation block 104, a roll rate sensor signal is generated from the roll rate sensor.

[0055]   In operation block 106, the reference roll angle is compared to the roll rate sensor signal. In operation block 108, a roll rate sensor fault signal is generated.

[0056]   In operation, a method for detecting a roll rate sensor fault includes generating a reference roll angle in an inertial frame with available signals other than roll rate, generating a roll rate sensor signal, compensating the roll rate sensor signal for all valid signal biases, comparing the reference roll angle to the roll rate sensor signal through a kinematics relation and a dynamic interaction related by a vehicle suspension, and generating a roll rate sensor fault signal.

[0057] While particular embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Accordingly, it is intended that the invention be limited only in terms of the appended claims.

Claims

1. A method for detecting a roll rate sensor fault comprising:

   generating a reference roll angle;
   generating a roll rate sensor signal;
   comparing said reference roll angle to said roll rate sensor signal; and
   generating a roll rate sensor fault signal in response to comparing said reference roll angle to said roll rate sensor signal.

2. A method as recited in claim 1 further comprising compensating for a valid signal bias in said roll rate sensor signal.

3. A method as recited in claim 2, wherein compensating for a valid signal bias further comprises adjusting an electrical long term bias over time with a minute adjustment at each sampling time or a sliding mode control.

4. A method as recited in claim 2, wherein compensating for a valid signal bias further comprises adjusting a mechanical long term sensor alignment pitch angle with a minute adjustment at each sampling time during vehicle turning or a sliding mode control during vehicle turning.

5. A method as recited in claim 2, wherein compensating for a valid signal bias further comprises halting roll rate sensor signal compensation in response to a fault flag or in response to a situation where compensation is unnecessary.

6. A method as recited in claim 1, wherein generating said reference roll angle further comprises sensing at least one of lateral acceleration, yaw rate, vehicle longitudinal speed, vehicle roll angle, wheel speed, or a GPS.

7. A method as recited in claim 1 further comprising refining said reference roll angle through steering wheel angle information to reduce a negligence error of a lateral velocity derivative.

8. A method as recited in claim 1 further comprising refining said reference roll angle with a calculation of a dynamic relation between a vehicle lateral acceleration and a suspension roll motion.

9. A method as recited in claim 1, wherein comparing said reference roll angle to said roll rate sensor signal comprises comparing a low pass filter version of a derivative of said reference roll angle with said roll rate sensor signal.

10. A method as recited in claim 1, wherein comparing said reference roll angle to said roll rate sensor signal comprises comparing a high pass filtered reference roll angle with a high pass filtered version of an integration of said roll rate sensor signal.

11. A method as recited in claim 1, wherein comparing said reference roll angle to said roll rate sensor signal comprises comparing said reference roll angle and said roll rate sensor signal through building a filter utilizing both a suspension dynamics and a kinematics relationship between roll angle and roll rate.

12. A method as recited in claim 1, wherein comparing said reference roll angle to said roll rate sensor signal comprises comparing said reference roll angle to said roll rate sensor signal through an observer that utilizes a kinematics relation and a dynamics relation.

13. A method as recited in claim 1, wherein comparing said reference roll angle to said roll rate sensor signal further comprises utilizing generating a dynamic bias estimate with a logic having said vehicle roll rate signal averaging to zero over a long period of time.

14. A method as recited in claim 1, wherein generating said roll rate sensor fault signal further comprises generating a lateral acceleration signal;

filtering said lateral acceleration signal;
generating a filtered lateral acceleration signal;
high pass filtering said roll rate sensor signal;
generating a filtered roll rate sensor signal; and
comparing said filtered lateral acceleration signal to said filtered roll rate sensor signal.

15. A method as recited in claim 1 further comprising shutting down a safety system in response to roll rate sensor fault or error.

16. A method as recited in claim 1 further comprising generating a substitute signal for said roll rate signal in response to roll rate sensor fault.
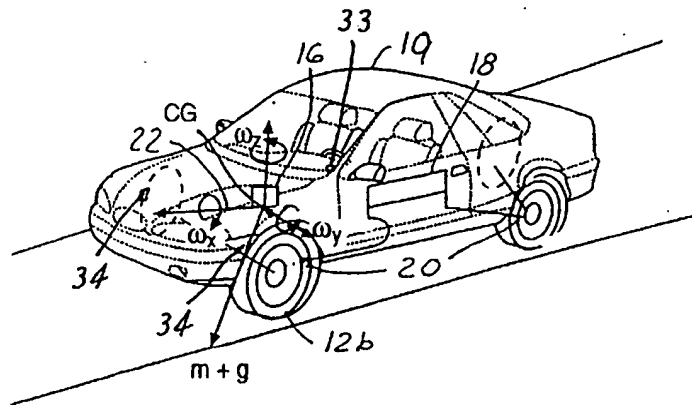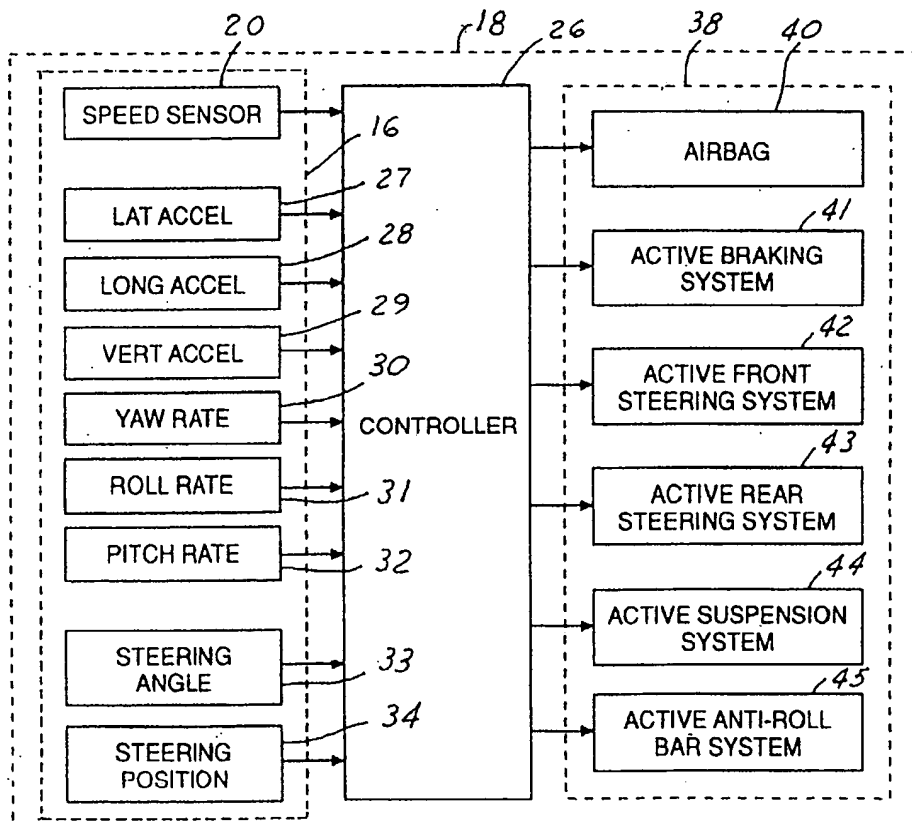
FIG. 1

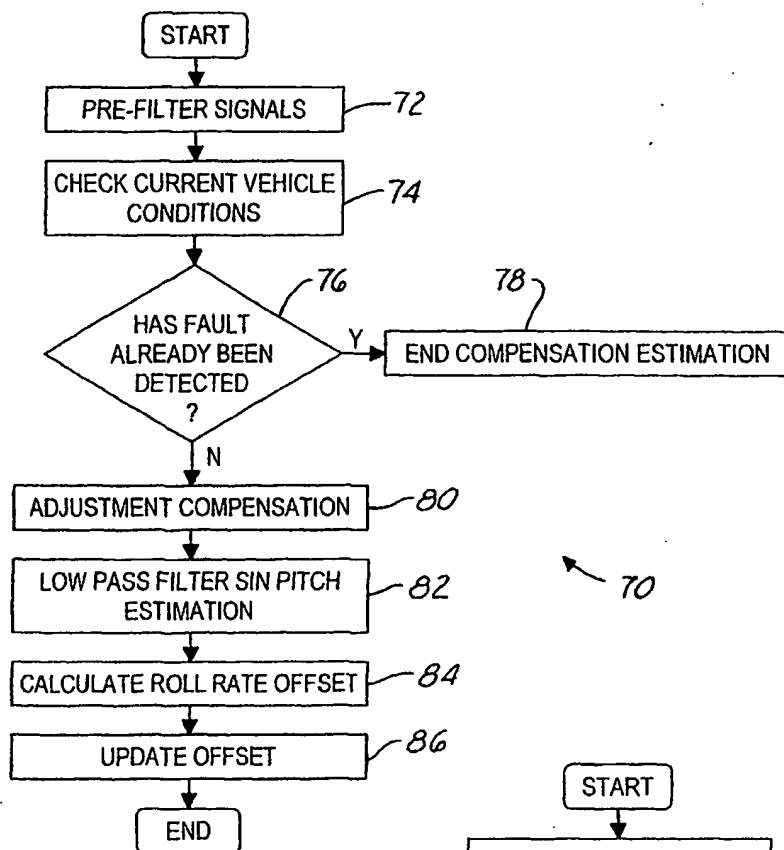
FIG. 2

START

PRE-FILTER SIGNALS —72

CHECK CURRENT VEHICLE
CONDITIONS —74

HAS FAULT
ALREADY BEEN
DETECTED
? —76

78

Y → END COMPENSATION ESTIMATION

N

ADJUSTMENT COMPENSATION —80

70

LOW PASS FILTER SIN PITCH
ESTIMATION —82

CALCULATE ROLL RATE OFFSET —84

UPDATE OFFSET —86

END

FIG. 3

START

102— GENERATE REFERENCE
ROLL ANGLE

104— GENERATE ROLL RATE
SENSOR SIGNAL

106— ADJUSTMENT COMPENSATION

100

108— CALCULATE ROLL RATE OFFSET

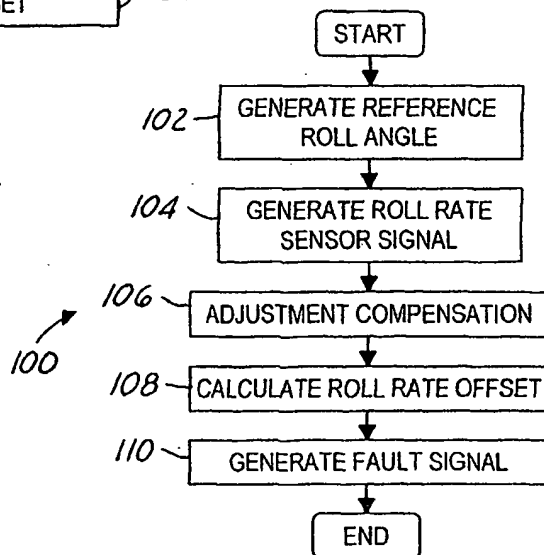110— GENERATE FAULT SIGNAL

END

FIG. 4

European Patent
Office

EUROPEAN SEARCH REPORT

Application Number

EP 03 25 4788

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
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The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
MUNICH	11 November 2003	Springer, O

ANNEX TO THE EUROPEAN SEARCH REPORT
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This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
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